A Study on Grinding Path Concatenation Algorithms Based on Cyber-Physical Robotic Systems

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Abstract— **With the rapid development of Cyber-Physical Systems (CPS) in recent years, industrial robots have been widely applied in many fields especially grinding process. However, the traditional robotic manufacturing system requires skillful experts to teach the robot program and control the manufacturing quality. In order to connect all robot trajectories, our path concatenation algorithm is utilized to find the global concatenate trajectory. To compare the traditional robot teaching, the performance of the proposed algorithms is better than it, and the computational time is 0.45045sec. finally, this paper has shown our Cyber-Physical robot grinding system is developed to grind the workpieces with complex shape surfaces successfully.**

I. INTRODUCTION

With the rapid development of Cyber-Physical Systems (CPS) in recent years, industrial robots have been widely applied in many fields such as cargo handling, welding, spraying, etc [1]. Cyber-Physical Systems in manufacturing are the integration of information technology (IT), communication technology (CT) and operational technology (OT) [2]. Hence, this methodology allows network of components including sensor, robot and other machines to share their information that can simultaneously transfer to the cyber twin in order to automated programming, configuring and optimization. As manufacturing is a labor-intensive and high-risk industry, the laborers produce the products under the environment which is filled with noise and seriously industrial dust pollution. Hence, the factories must face the labor shortage problem. In order to solve the shortage of human resources, Taiwan's water faucet industry needs to develop the procedures for the intelligent grinding and polishing system. A Cyber-Physical robot cell (CPRC) plays an important role in the grinding and polishing processes [3]. The information can be closely connected and synchronized between the physical shop floor and the cyber computational space. Therefore, the virtual robot system can help to generate and analyze trajectory of the grinding and polishing processes automatically. For the previous work related to CPS applied in manufacturing, Luo and Kuo [4] presented a service-oriented multiagent system for the control and analysis of the CPSs in manufacturing automation utilizing a noncontact dynamic obstacle avoidance 7-DoF robot arm. Villalonga et al. [5] proposed an industrial CPS architecture for condition-based monitoring to manage alarm and events combining local information in order to predict failure pattern in CNC machine tools. Generally, it assumes that the computer-aided design and computer-aided manufacturing (CAD/CAM) system can be part of cyber twin and apply to automatically generate the toolpath of workpiece and desired robot movement. However, the installation of robot and workpiece would cause the position and orientation errors that compare to ideal simulation layout. To resolve these problems, the force control algorithms such as the impedance control, hybrid control have been proposed. The force control can receive force data and apply feedback control to adjust trajectory according to ideal CAD/CAM information [6]. In the robot simulation procedures, path planning is key element that need to find a collision-free, continuous sequence of feasible actions, or path segments, from the start to the goal position. Sampling-based planning (SBP) have been successfully used to solve high dimensions of the search space. This randomized approach has its advantages in terms of providing fast solutions for difficult problems [7]. The most commonly used methods in robotics are the Probabilistic Roadmap Method (PRM) [8] and the Rapidly-exploring Random Tree (RRT) [9]. Kingston et al. [10] presented a formulation of the algorithms used by the projection- and continuation-based space representations, this allows a broad class of sampling-based planners to plan with constraints without any special limitation.

For robotic grinding process, there are three main parts that must be well-designed: calibration of the system [11], path planning of the workpieces and robots [12], and virtual methodology to evaluate the performance and quality [13]. Besides, due to the trend towards big data points out that storing data for later use can be valuable and beneficial [14], the CPS and big data are two keys for Industry 4.0 in the near future. Consequently, constructing a database to store the data during manufacturing is important and necessary in smart manufacturing. The recorded data from internal controllers or external sensors provide rich information, for example, the data from F/T sensor can help accomplish robot force control [15], and by analyzing the acoustic emission (AE) signal from AE sensor, it can monitor the condition of the process [16].

Based on our previous work in [17], The aim of this paper is to develop a new framework of grinding robot system with advanced CPS which is able to monitor and connect between physical shop floor and the cyber computational space. The CAD/CAM system can apply the vision-based calibration method to locate peripheral device's position and orientation. Moreover, the robot trajectories can be automatically refined and connect by path concatenation algorithm to reduce time of process setting and maintain workpiece quality. The database

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is constructed to analyze abrasive belt wear-life using acoustic emission (AE) signal during the grinding process.

II. SYSTEM STRUCTURE

A. Hardware Architecture

Our grinding robot with Cyber-Physical Systems which is consisted of a 6-axis Fanuc industrial robot (M-710iC/50E), grinding machines as shown in Fig.1. For monitoring the grinding process, a balance system acoustic emission (AE) sensor, 9SAESNG0030000, is installed on the gripper. The 3D camera is mounted on the gripper with eye-to-hand configuration to collect both the geometry and color of the object. Besides, our system use two abrasive belts #100 and abrasive belts #280 to grind the workpieces in order to obtain enough roughness.

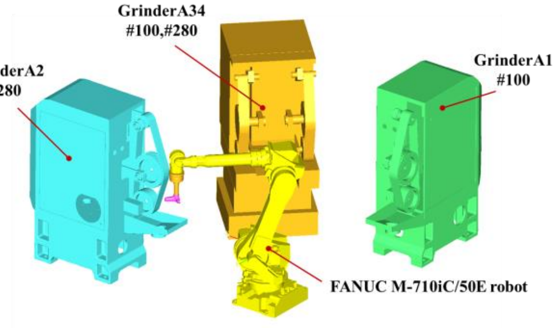


Fig.1. Hardware setup of the Cyber-Physical robot system.

B. Software Architecture

In this research, the software flowchart is outlined in Fig.2 assuming the cyber and physical system are already connected by communication. First of all, the toolpath generation is used to generate toolpath using CAD model. In addition, the hand-eye calibration could help to find the relationship between the 3D camera and robot. To locate the real position and orientation of the grinding machine, the machine localization could be used to achieve the Cyber-Physical integration. Then, the robot trajectory generation could be transformed through real environment layout. Besides, the limitation avoidance would check the limitations of 6-axis industrial robots such as robot joint limit, singularity and object collision. However, the different combination of trajectories needs to connect by manual setting. Therefore, the robot trajectory concatenation method could find collision-free strategy to connect different trajectories. Finally, the sensor system can collect information during the grinding process that can be analyzed by the proposed software such as the abrasive belt wear-life algorithm.

III. RELATIVE THEORIES

A. System Initialization

To start of the Cyber-Physical robot grinding system, system initialization must be done at first. The CAD/CAM offline programming was developed to automatically generate the toolpath of workpiece. The principal of toolpath generation in the simulator is based on iso-planar method [18].The toolpaths are generated by intersecting surface in Cartesian space and are calculated based on a zigzag path with a uniform interval between adjacent toolpaths as shown in Fig.3.

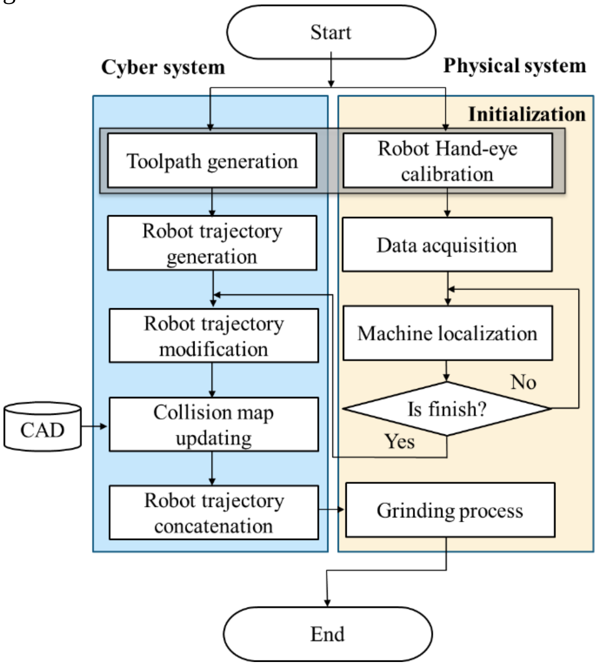


Fig.2. Software flowchart of the Cyber-Physical robot system.

The other essential factor in grinding process is to calibrate the posture of the robot hand-eye beforehand. This research adopts a scheme of using a sensory 3D camera as eye-in-hand configuration to positioning and orientation of grinding machine. Before locating the grinding machine, the rigid transformation between the camera frame and the robot end-effector must be computed in advance and such issue was already formulated by [19].

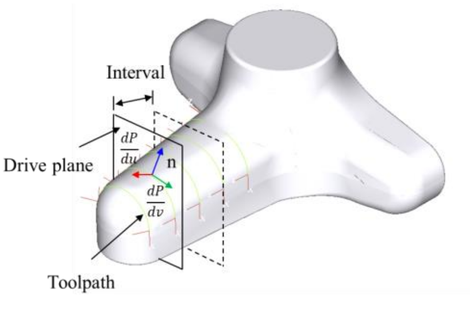


Fig.3. The iso-planar toolpath generation.

B. Robot Trajectory Modification

Before robot Trajectory modification procedure, a machine localization approach for calibrating the grinding machine position precisely was proposed by our previous work [17]. Our method could eliminate uncertainty between reality and simulation word. Following the calibration results of machine location, the robot trajectory could be updated in the real-time. Then, the CAD/CAM offline programming would check the limitations of 6-axis industrial robot such as robot joint limit, singularity and object collision. Additionally, our offline programming provided the interface to adjust robot posture called configuration transformation matrix. To apply the configuration transformation matrix, the robot posture could gain extra transformation to prevent limitations and maintain constant contact force during process according to the transformation equation [17].After that, the robot trajectory could be imported into the real robot controller.

C. Robot Trajectory Concatenation

In order to connect different trajectories, Rapidly-Exploring Random Trees (RRT) is utilized to find a global path in the configuration space. RRT is a sample-based single-query path planning algorithm which can quickly search high dimensional spaces. The Sampling-based planners provide the two desirable properties. The one is probabilistic completeness (PC), the other is Asymptotic optimality (AO). Before connecting robot trajectory, the collision map must be updated by using real environment information. Our collision map uses the octomap [20] to fuse CAD model and sensing environmental data. To compare only using CAD model, our advantage is to consider changes of environment. It uses probabilistic occupancy estimation to represent occupied space and free areas. Fig.4 shows the flowchart of robot trajectory concatenation. The first, CAD and sensing data need to update the octomap. After that, collision model must be determined to check collision between two objects. To speed up the procedure of collision detection procedure, it is composed by two main parts: broad-phase and narrow-phase. In the broad-phase, it's based on the comparison of the overall bounding volumes of objects to determine if they are in collision or not. In this research, we use the Oriented-Bounding-Box (OBB) bounding volume. Before running RRT planner, the start and end configuration must be determined in advance. Finally, we can find the concatenate trajectory to connect trajectory A and trajectory B.

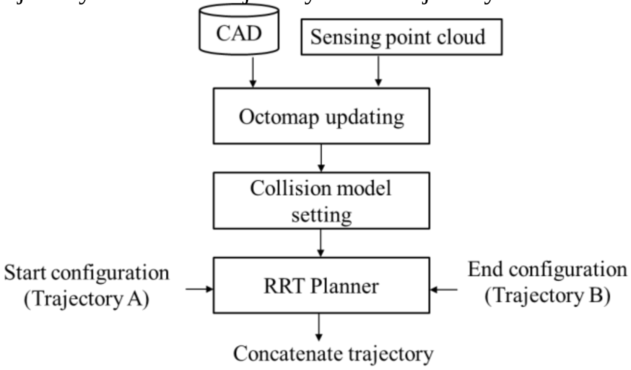


Fig.4. The flowchart of robot trajectory concatenation

IV. EXPERIMENT AND ANALYSIS

A. Trajectory Generation Results

In the experiment, HCG brass faucets (product type: 3720) as shown in Fig.5 (a) was processed by our grinding robot system that consisted of a 50kg payload robot, two fixed grinding machines and a rotated grinding machine as shown in Fig.5 (b).

(a) (b)

Fig.5. (a) HCG brass faucets (product type: 3720). (b) Fanuc M-710iC/50E grinding robot cell.

B. Robot Trajectory Modification Results

The grinding machine localization results are illustrated inFig.6. The green one is the point cloud of sensing data, and the red one is the point cloud of CAD model. Using the grinding machine localization, the result of robot grinding trajectory modification can be generated by configuration interface in Fig.7 (a). As shown in Fig.7 (b), the blue line represents the result of robot configuration in grinding path, which has avoided the collision (pink contour), joint limit (purple contour), and singularity (orange contour).

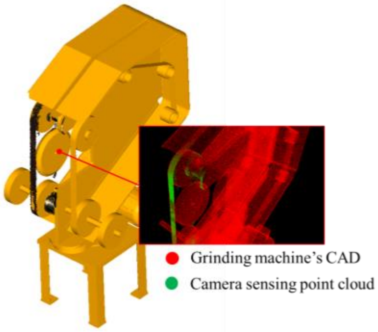
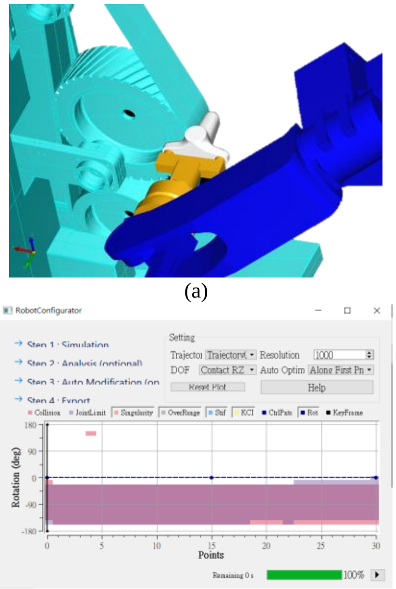


Fig.6. The grinding machine localization results


(a)

Trajector Trajectory(
Resolution 1000
DOF Contact RZ
Auto Optim Along First Pn

(b)

Fig.7. (a) Robot trajectory modification results, (b) Robot configuration interface in grinding path.

C. *Robot Trajectory Concatenation Results*

The robot trajectory modification can help to generate and modify transformation matrix including translation and rotation. However, HCG brass faucets (product type: 3720) have to use six trajectories to reach whole coverage rate. These trajectories need to be connected by manual check. It can't guarantee to find the shortest concatenate trajectory between two trajectories. Therefore, RRT path planner are applied to find collision-free and the shortest path in cyber space. There are many sample-based path planning algorithms such as PRM, RRT, EST. To evaluate computation time, we select the last point of path 1 as start configuration and the first point of path 2 as end configuration. Fig.8 shows the comparison of the SBP algorithms. The result shows that EST algorithm is faster than RRT algorithm.

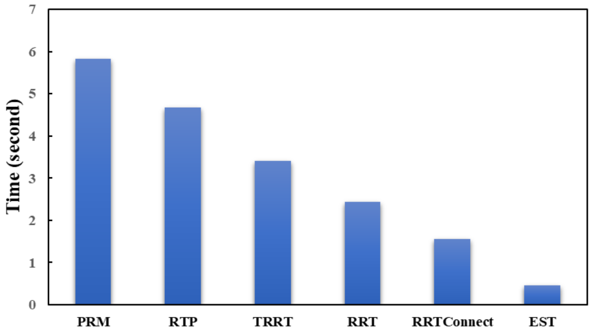


Fig.8. The comparison of the SBP algorithms

V. CONCLUSION

This paper has shown the Cyber-Physical robot grinding system is developed to grind the workpieces with complex shape surfaces successfully. Based on sampling-based planning concept, the trajectories of workpiece can be connected by path concatenation algorithm and the global path can be found in the configuration space. In order to eliminate the uncertainty between the real and simulation world, the machine localization can locate the machine's position information precisely. Therefore, the robot trajectory can be generated and modified automatically to avoid robot joint limit, singularity and collision. RRT and EST path planner were applied to find the concatenate trajectory between two trajectories, and the computational time is 0.45045sec. The result shows that EST algorithm is faster than RRT algorithm. Finally, we applied AE signal to monitor grinding process conditions.

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